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Thermal Analysis of a Compound Parabolic Collector

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Abstract : ***Solar energy is a proven, yet underdeveloped, clean energy resource. In the last few decades, considerable research has gone to lower the cost of its production and improve the efficiency of standard solar collectors such as concentrating collectors. A Compound Parabolic Collector is a non imaging Concentrator. It is easy to fabricate, operate and cost is low compared to other available concentrating collector systems. The Compound Parabolic Collectors are used in this analysis as a non-imaging concentrator whose axes are inclined to each other. Its two parabolic segments above the focal point are removed and those below the focal point were selected. The length of the collector is 1m and having an aperture width of 0.96m. The receiver pipe inner diameter is 0.0381m. The collector selected is aimed to withstand a steam temperature of 150 ^{o} C. In this thesis the performance analysis of a compound parabolic collector is evaluated. And a comparison of its performance is drawn between two Indian cites Visakhapatnam and Mumbai by taking the solar radiation data from the Indian Meteorological Department for the two cities. The performance evaluation of the system shows potential of improving the thermal efficiency up to 75%. From the obtained results, graphs are drawn to assess the performance of the compound parabolic collector.***

Keywords: Acceptance Angle, Solar Radiation, Compound Parabolic Collector, Useful Heat Gain.

1 INTRODUCTION

The increasing cost of fossil fuels and that of the electricity resulting into increased CO_2 emissions is causing environmental problems and has made our society turn towards renewable energy sources. Solar energy utilization is a promising way to fulfil large part of worldwide energy demand in various ways.

The conventional flat plate collectors (FPC) are widely used for domestic hot water production and for low temperature applications (30–90^{0}C). Concentrating collectors with high concentrating ratios operate in high temperature levels (300–400^{0}C) by giving suitable heat for electricity production in power plants. Parabolic trough collectors (PTC), Fresnel collectors, central tower receivers and parabolic dish Stirling engines are the main solar technologies used in electricity production. Industrial and residential applications operate in intermediate temperature range (100 ^{0}C to 300 ^{0}C) temperature limits. Applications such as industrial process heating, space cooling with absorption technology, oil extraction and low temperature electricity production is most suitable. The solar collector employed under these conditions is the compound parabolic collector (CPC) with evacuated tube which is able to use the processed heat efficiently.

Several researchers discussed performance of different types of compound parabolic collectors used for different purposes Zimmerman et al.[1] in their article have tried to push small thermal collectors to an extreme with a portable, flat panel, vacuum packaged “micro” solar collector design for hydrogen production and the maximum (stagnation) experimental temperature achievable was approximately 300 ^{o} C. However, without concentration, 300^{o} C is only achieved at stagnation. In order to increase the collector efficiency for methanol reforming, a concentrating solar collector is necessary.

Rabl [2] in his paper has developed a mathematical model for the average number of rays reflections in a compound parabolic collector, something very important for the optical analysis. Studies for compound parabolic collector with non-evacuated tubes for thermal performance have been made in order to predict the efficiency in various operating conditions. The use of evacuated tubes was first analyzed in Argonne National Laboratory before 1980. Snail in 1984 analyzed an integrated stationary compound parabolic collector with evacuated tube. The final results proved an optical efficiency of 65% and a thermal of 50%.

Singh et al. [3] in their article made a very interesting review about integrated collector solar water heaters stating the novelties that are able to increase their efficiency. These systems include compound parabolic reflectors, phase change materials and special materials (absorber and cover) in order to achieve high daily performance.

Chaabane et al. [4] in their article had numerically examined the thermal performance of an integrated collector storage solar water heater (ICSSWH) using the numerical software FLUENT 6.3. This study reveals that the coverage of the storage tank with a glass tube is an efficient solution to improve the performance of the ICSSWH, and mainly its thermal losses. Indeed, numerical simulations results show that this modified design is having higher water temperature and lower thermal losses during all the day. The air gap spacing between the storage tank and the covering glass tube is also optimized to maximize the thermal output and minimize the thermal losses and CFD results show that the optimal performance corresponds to the lowest air spacing (L=0.005 m). Smyth et al. [5] in their article have investigated an inverted absorber of integrated collector storage solar water heater (ICSSWH) mounted in the tertiary cavity of a CPC with a secondary cylindrical reflector and indicated the optimum baffles location for thermal losses reduction through convection suppression

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Tripanagnostopoulos et al. [6] in their paper had fabricated an asymmetric CPC collector with two separate absorbers in order to absorb and trap maximum solar radiation. At the same time they made the system cost effective compared to flat plate collector using low cost material, but with lower concentration and working fluid temperature less than 100 ^{0}C. Karagior et al. [7] in their paper have explored the potential for application of solar thermal systems in sectors such as food industry, agro-industries, textiles and chemical industry. In this paper, these systems were evaluated in economic terms in comparison with energy equivalent systems. Design and material quality requirements for solar systems in these industrial applications were studied. Design for collectors, absorbers and storage tanks were studied. Various current applications were reviewed and their inadequacies were also explained. After the review it was observed that installation of different solar harvesting devices such as solar dryer, parabolic trough system and flat plate collectors for different applications can be economically attractive for the users. He also proved that use of such systems offer significant energy savings and provides environmental benefits to the society.

Eshan and Kishore [8] in their paper evaluation of various parameters of a compound parabolic collector have analyzed a compound parabolic collector for Visakhapatnam location

Gudekar et al. [9] in their paper have experimentally demonstrated a low cost compound parabolic collector requiring single tilt adjustment a day.

Oommen et al. in their article have designed a steam generation system incorporated with a pressure cooker powered by compound parabolic solar collectors with half-acceptance angle of 23.51. The result shows that the efficiency of the system was about 50%.

2 Description and Working of a Compound Parabolic Collector

2.1 Description

A compound parabolic collectors has the highest possible concentration permissible by thermodynamic limit for a given acceptance angle. Its large acceptance angle results in intermittent tracking towards the sun. A compound parabolic collector is mostly orientated with its long axis along the east–west direction and for a location in northern hemisphere; its aperture is tilted towards south for most of the time of the year, such that the sun rays are incident on compound parabolic collector aperture within the acceptance angle. The tilt of the compound parabolic collector may have to be adjusted periodically when the incident solar radiation moves outside the acceptance angle of the collector.

2.2 CPC's basically consists of three elements:

1. Receiver: The receiver should have the highest absorptance for solar radiation as possible and must be constructed with high-conductivity metals in order to conduct efficiently the absorbed heat into the heat transfer fluid. Most receiver materials do not have a very high absorptance, and they need to be covered with special solar selective surface coatings. A selective commercial solar coating like Solkote (Make: Solec, US) these losses can be reduced substantially (Absorptivity=0.9137 and emissivity=0.244) was applied on the surface of the receiver. For good absorptivity, receiver should be cleaned properly. It is a very complex but crucial part of the collector.

2. Cover: The ideal cover is a transparent insulation that allows the passage of solar radiation to the reflector and receiver, having a high transmittance of solar radiation, and a low transmittance of the thermal radiation from the receiver; also, it must have high durability and low cost.

3. Reflector: Usually the non-imaging reflectors are CPC reflectors. It is made up of a metal sheet with high reflectivity (90% to 95%). Reflector reflects maximum amount of sun's radiation towards the receiver. Reflector should be cleaned frequently in order to achieve good reflectivity. Its function is to focus beam-solar radiation onto the receiver, which is located at the focus of the system. Two MS sheet segments were used to construct the reflector sides. In order to achieve the best CPC performance, each material component was carefully selected. The general Concentration Ratio for a CPC is around 3 –10.

Specification	**unit**	**value**
Aperture surface area	m^2	.96
Reflectivity	%	95
Reflector material	Mild steel	
Reflector type	Compound parabola	

Table 2.1: Reflector specifications

2.2 Working of a compound parabolic collector

Compound parabolic concentrator (CPC) is an ideal solar energy collector. It can collect and focus a larger area of sun light onto a smaller area with minimum loss.Compound parabolic collector (CPC) is a well-known kind of non-imaging collector. In CPC, parallel light rays get focused at two points instead of one. The name, Compound Parabolic Concentrator, derives from the fact that it is comprised of two parabolic mirror segments with different focal points as indicated in figure. The focal point (B) of 1st parabola lies on 2nd parabola, whereas the focal point (A) of 2nd parabola lies on 1st parabola. The two parabolic surfaces are symmetrical with respect to reflection through the axis of the CPC.

Compound parabolic concentrators can accept incoming radiation over a relatively wide range of angles. By using multiple internal reflections, any radiation that is entering the aperture, within the collector acceptance angle, finds its way to the absorber surface located at the bottom of the collector. The absorber can be cylindrical or flat.

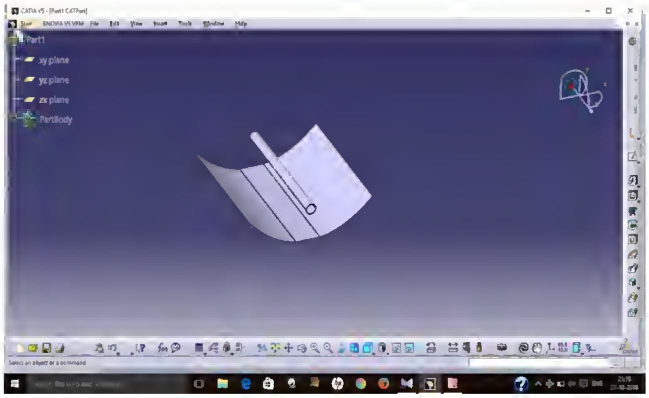

Fig.1: Basic Shape of a Compound Parabolic Collector

3.9 Instrument for Measuring Solar Radiation

The instrument used in measuring solar radiation is pyranometer or a pyreheliometer.

A pyranometer is an instrument which measures either global or diffuse radiation falling on a horizontal surface over a hemispherical field of view. Basically the pyranometer consists of a black surface which heats up when exposed to solar radiation. Its temperature increases until the rate of heat gain by solar radiation equals the rate of heat loss by convection, conduction and radiation. The hot junction of a thermopile is attached to the black surface, while the cold junctions are located under a guard plate so that they do not receive the radiation directly. As a result an emf is generated. This emf which is usually in the range of 0 to 10 mV can be read, recorded or integrated over a period of time and is a measure of the global radiation. An accuracy of about ±2 percent can be obtained with the instrument.

The pyranometer can also be used for the measurement of diffuse radiation. This is done by mounting it at the centre of a semicircular shading ring. The shading ring is fixed in such a way that its plane is parallel to the plane of the path of the sun's daily movement across the sky and it shades the thermopile element and the two glass domes of the pyranometer at all times from direct sunshine. Consequently, the pyranometer measures only the diffuse radiation received from the sky.

A pyreheliometer is an instrument which measures beam radiation falling on a surface normal to the sun's rays.

3 Analysis of Compound parabolic collector

3.1 Geometry of collector

Half acceptance angle $(\theta_a) = \sin^{-1}(1/C)$ (3.1)

The concentration ratio of the collector is given by

$$C = W/b = \frac{\text{Aperture width}}{\text{Absorber width}}$$

(3.2)

The surface area of the concentrator is by integrating along the parabolic arc.

$$\frac{A_{conc}}{WL} = \sin\theta_a\,(1+\sin\theta_a)\left[\frac{\cos\theta_a}{\sin^2\theta_a} + \ln\left\{\frac{(1+\sin\theta_a)(1+\cos\theta_a)}{\sin\theta_a[\cos\theta_a+(2+2\sin\theta_a)^{1/2}]} - \frac{\sqrt{2}\cos\theta_a}{(1+\sin\theta_a)^{3/2}}\right\}\right] \quad (3.3)$$

(or)

$$\frac{A_{conc}}{WL} = 1 + C$$ For the concentration ratio value $C > 3$

(3.4)

3.2 The Declination (δ)

δ is given by $\delta = 23.45 \sin\left[\frac{360}{365}(284 + n)\right]$ (3.5)

Where n is the day of the year.

3.3 Heat Transfer Coefficient on the inside surface of the Absorber Tube (h_{ci})

The heat transfer coefficient may be calculated from Dittus - Boelter equation.

$$Nu = 0.023 * Re^{0.8} * Pr^{0.4} \quad (3.6)$$

3.4 Solar Radiation on Tilted Surfaces

3.4.1 Beam Radiation

For the case of a tilted surface facing south ($\gamma=0^0$).

$$\cos\theta = \sin\delta\sin(\phi-\beta) + \cos\delta\cos\omega\cos(\phi-\beta) \quad (3.7)$$

While for a horizontal surface

$$\cos\theta_z = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega \quad (3.8)$$

$$r_b = \frac{\cos\theta}{\cos\theta_z} = \frac{\sin\delta\sin(\phi-\beta) + \cos\delta\cos\omega\cos(\phi-\beta)}{\sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega} \quad (3.9)$$

3.5 Total effective flux entering the aperture plane

The total effective flux entering the aperture plane is

$$S = [I_b r_b + I_d/C]\,\rho_e\,\tau\,\alpha \quad (3.10)$$

3.6 Effective Reflectivity (ρ_e)

$$\rho_e = \rho^m \quad (3.11)$$

Rabl has also shown that the average number of reflections m undergone by all radiation falling within the acceptance angle, before reaching the absorber surface, is given by the expression

$$m = \frac{1}{2\sin\theta a}\left(\frac{A_{conc}}{WL}\right) - \frac{(1-\sin\theta a)(1+2\sin\theta a)}{2\sin^2\theta a} \quad (3.12)$$

3.7 Overall loss coefficient (U_L)

Rabl has estimated the value of U_L for different values of the absorber plate temperature, plate emissivity and the concentration ratio. It is seen that they vary from 4 to 19.4 W/m^2. Values of U_L for different situations can be obtained by interpolation.

3.8 Collector efficiency factor (F`)

$$\frac{1}{F'} = U_l\left[\frac{1}{U_l} + \frac{b}{N\pi D_i h_f}\right] \quad (3.13)$$

3.9 Heat Removal Factor (F_R)

$$F_R = \frac{m' c_p}{bU_l L}\left[1 - \exp\left(\frac{-F' bU_l L}{m' c_p}\right)\right] \quad (3.14)$$

3.10 Useful heat gain rate

$$(q_u) = F_R WL\left[S - \frac{U_l}{C}(T_{fi} - T_a)\right] \quad (3.15)$$

3.11 Heat transfer rate

$$q_u = mc_p\Delta T = m \times c_p \times (T_{fo} - T_{fi}) \quad (3.16)$$

3.12 Thermal Efficiency

The instantaneous efficiency can be calculated on the basis of beam radiation

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$$\eta = \frac{q_u}{A_a \times I_b} \quad (3.17)$$

4. Results and Discussions

The Compound Parabolic Collector was analyzed for two different cites Visakhapatnam and Mumbai and accordingly graphs were plotted from the obtained results.

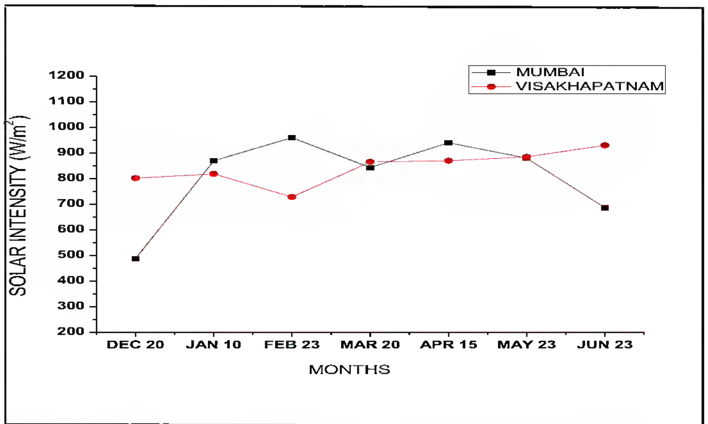

Fig.4.1: Variation of solar intensity over Visakhapatnam and Mumbai

Fig.4.1 shows the variation of solar intensity over Mumbai and Visakhapatnam for a period of seven months from December 2015 to June 2016. The solar intensity varies from 801.67 W/m^2 in December to 930 W/m^2 in June for Visakhapatnam and 488.33 W/m^2 in December to 686.67 W/m^2 in June for Mumbai. From the graphs we can infer that the solar intensity over Mumbai is highly varying when compared to Visakhapatnam where the variation is less.

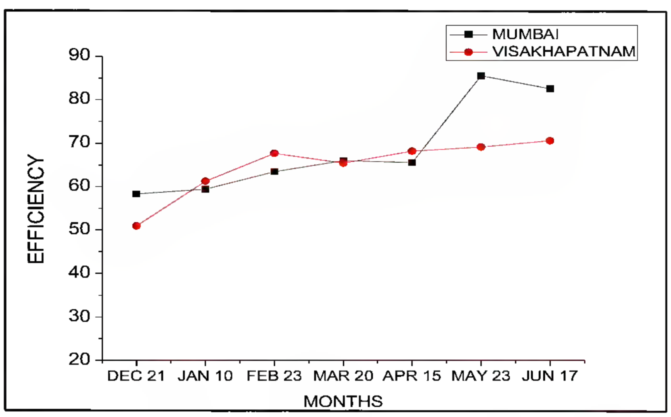

Fig.4.2: Variation of Efficiency over Visakhapatnam and Mumbai

Figure 4.2 shows the variation of Efficiency over Mumbai and Visakhapatnam for a period of seven months from December 2015 to June 2016.The efficiency increases from 50.94% to 70.55% for Visakhapatnam and 58.29% to 82.5% for Mumbai locations respectively. May and June months have showed a maximum deviation of 14%

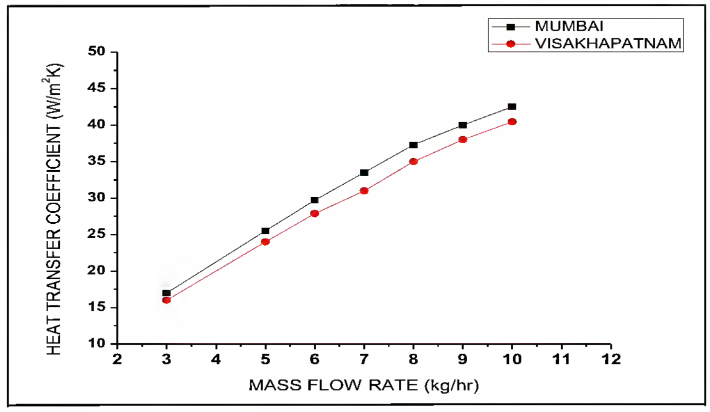

Fig.4.3: Variation of Heat transfer coefficient to mass flow rate

Figure 4.3 shows that variation of heat transfer coefficient with mass flow rate. And the results obtained show that with increase in mass flow rate from 3 kg/hr to 10 kg/hr heat transfer coefficient also increases from 17W/m^{2}K to 42.5W/m^{2}K for Mumbai and 16W/m^{2}K to 40.45W/m^{2}K for Visakhapatnam. Therefore it is clear that heat transfer coefficient increases with increase in mass flow rate due to increase in temperature difference.

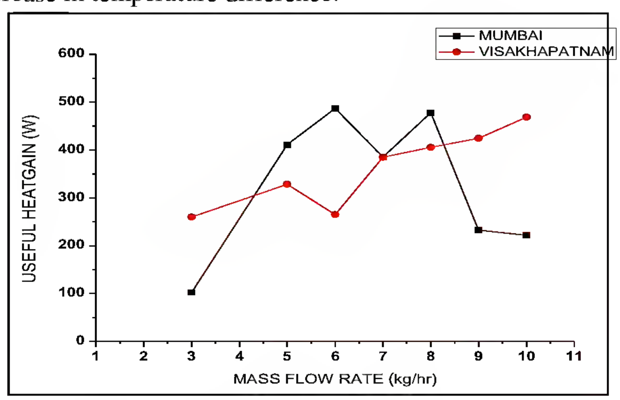

Fig.4.4: Variation of useful heat gain rate to mass flow rate

The above figure shows the variation of useful heat gain at different mass flow rates. Results show that with increase in mass flow rate from 3 kg/hr to 10 kg/hr useful heat gain rate varies from 102.59 W to 221.74 W for Mumbai and varies from 260 W to 468.45 W for Visakhapatnam respectively. From the graph it is observed that compared to Mumbai Visakhapatnam has 9.4% more useful heat rate.

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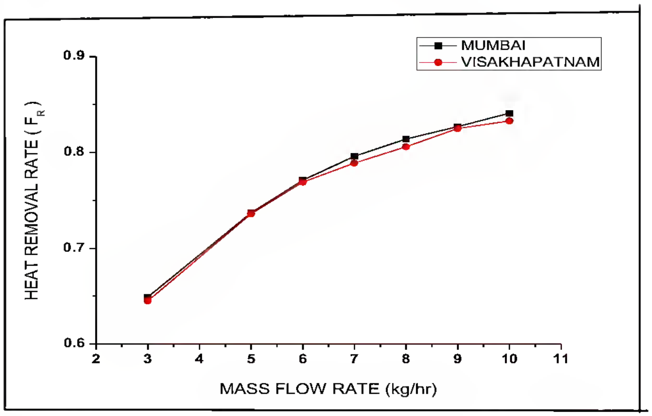

Fig.4.5: Variation of heat removal factor with mass flow rate

The above graph shows the variation of mass flow rate and heat removal factor. The results obtained show that with increase in mass flow rate from 3 kg/hr to 10 kg/hr the collector heat removal factor also increases from 0.65 to 0.84 for Mumbai and 0.65 to 0.833 for Visakhapatnam respectively. The heat removal factor remains almost same for both the locations.

5 Conclusions

From the performance evaluation done on the CPC it can be concluded that the analyzed CPC worked reasonably well for steam generation at atmospheric pressure. Moreover the overall system cost has been reduced. With more refinements in the design and scale up would further enhance the system performance and will enable steam generation at temperatures at which significant fraction of process heat can be used.

From the comparison of the performances of the solar collector at Mumbai and Visakhapatnam following conclusions can be drawn.

- The solar intensity is highly fluctuating for Mumbai location during the months of December and June, while for Visakhapatnam the solar intensity is almost same except for the month of February.
- The Efficiency of the collector for these locations is almost similar for most of the months except May and June, for which collector placed at Mumbai has 14% higher efficiency than that of Visakhapatnam.
- The heat transfer coefficient increases with mass flow rate (due to increase in temperature difference) for both the places, with Mumbai having 5% higher heat transfer coefficients than Visakhapatnam.
- The useful heat gain rate is just as fluctuating as the solar intensity at these places, but Visakhapatnam has 9.4% more useful heat gain rate than Mumbai.
- The heat removal factor almost increases linearly with mass flow rate for both the locations with negligible variation.
- The collector efficiency can be optimized by optimizing fluid flow rate.

6 Nomenclatures

A_{conc} Surface Area of the Concentrator, m^2
b Absorber Surface Width, m
C Concentration Rau9tio
C_P Specific Heat of Water, J/kg K
D_i Tube Inner Diameter, m
D_o Tube Outer Diameter, m
F' Collector Efficiency Factor
F_R Heat Removal Factor
h_{ci} Heat Transfer Coefficient on inside surface of the tube. W/m^2K
k Thermal conductivity, W/m K
L Length of the Collector, m
m˙ Mass Flow Rate of Fluid, kg/hr
n Day of the year
N Number of Tubes
Nu Nusselt number
Pr Prandtl number
q_u Useful heat gain rate, W
r_b Tilt factor
Re Reynolds number
S Total effective flux entering the aperture plane

T_{fo} Water outlet temperature, $^{\circ}C$
T_{fi} Water inlet temperature, $^{\circ}C$
T_a Ambient Temperature, $^{\circ}C$
U_l Overall Loss Coefficient
W Aperture Width, m

Greek symbols

A absorptivity of absorber surface
β the slope
δ the declination angle
ε emissivity
η efficiency
μ viscosity, N s/m^2
ω hour angle
ϕ the latitude
ρ density, kg/m^3
ρ_e effective reflectivity
θ_a half acceptance angle
τ transmissivity of glass cover

Subscripts

a acceptance
conc concentrator
e effective
fo fluid outlet
fi fluid inlet
fm mean fluid
i inner
l loss
o outer
u useful

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